

# **Sediment Transport by Internal Waves in EUROSTRATAFORM**

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## **LONG-TERM GOALS**

The overall long-term goal of EUROSTRATAFORM is to advance our understanding of the development and modification of sedimentary deposits and sequences on continental terraces (shelves and slopes) in the Mediterranean Sea. Specifically, field studies of modern sedimentary processes will focus on two regions: along the central and northern Adriatic Sea off Italy, and in the Gulf of Lyons off southern France.

This project investigates the role that internal waves of various frequencies might have in affecting sedimentation in these two regions. The overall long-term project goal is to determine the modes and mechanisms of transport of bottom and suspended sediment by internal waves. The primary emphasis of the research is to examine the available and newly acquired information on internal waves and density structure in the northern Adriatic Sea and Gulf of Lyons, and to make estimates of internal wave effects on sedimentation in both regions.

## **OBJECTIVES**

- Evaluate the role of internal waves in resuspending and transporting sediment on the shallow sections of the Adriatic continental shelf off central Italy (water depths < 100 m) and on the shelf and slope off southern France.
- Develop relationships for estimating internal wave-induced bottom stresses that can be applied to sediment transport calculations.

## **APPROACH**

This project is primarily focused on the interaction of internal waves and the seabed. The approach will extend the internal wave-slope sedimentation model developed in STRATAFORM to EUROSTRATAFORM sites (Cacchione, et al, 2002). We are using historical and newly acquired data obtained during EUROSTRATAFORM field experiments to estimate internal wave effects on sedimentation. We will develop bottom stress expressions for internal wave boundary layers that can be used to predict sediment entrainment by internal waves, and that can be applied to modern sedimentation processes in both the Adriatic Sea (“PASTA”) and Gulf of Lyons. Additionally, we will assist with planning and coordination of field experiments in both study areas.

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This effort is aimed at three specific tasks: (1) continued development of the model for inhibited deposition and possible erosion by internal waves over sloping bottoms; (2) planning and coordination of field measurements in the Eurostrataform study areas; and (3) analysis of density profiles and current measurements to investigate internal wave and sediment dynamics in the study areas.

## WORK COMPLETED

- Characteristic angles (i.e., group velocity vector directions) have been calculated for internal waves of various frequencies using Brunt Vaisala frequencies determined from density profiles.
- Spectral analyses of velocity and temperature data from PASTA have been completed. The data were obtained on a mooring deployed in about 50 m water depth off Pescara, Italy by Spanish scientists. In particular, analysis of velocity and temperature data showed energetic motions at near-inertial and higher internal wave frequencies.
- Progress toward deriving estimates of bottom shear by near-inertial and high frequency internal waves has been made.
- Analysis of spatial scales of crenulated bedforms (in the PASTA region) and internal wave-induced bed shear zones was initiated.

## RESULTS

The effects of internal waves and tides on transport of bottom and suspended sediment are poorly understood. We have approached this problem both theoretically and using new data collected during the first EUROSTRATAFORM field experiment.

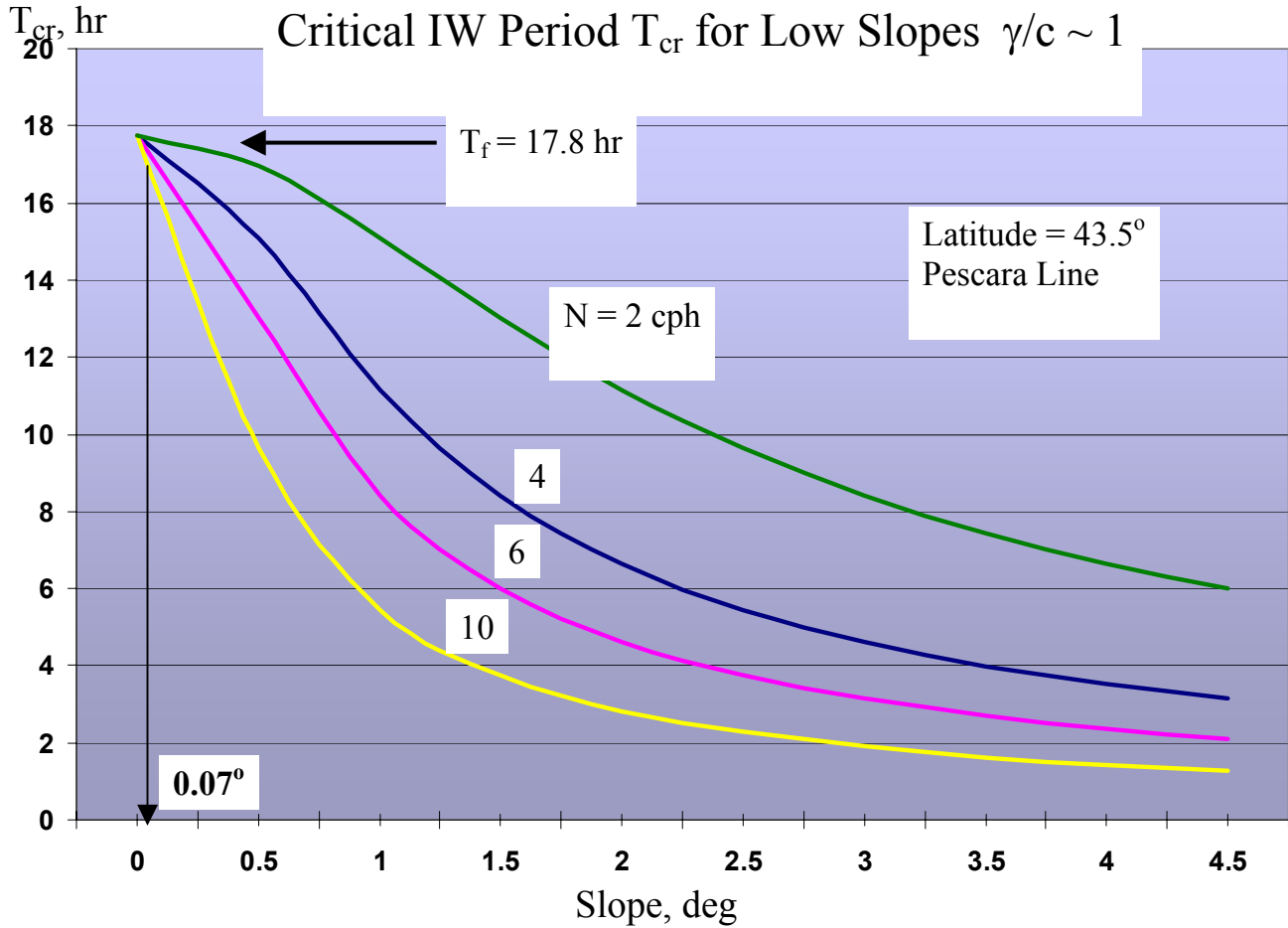
Internal wave group velocity vectors (often called “characteristics”) travel at an angle  $c$  to the horizontal that is determined by the frequency of the internal waves, the density profile, and latitude (Cacchione and Drake, 1986). This angle is given by:

$$c = \left( \frac{\sigma^2 - f^2}{N^2 - \sigma^2} \right)^{1/2} \quad (1)$$

The highest velocities and shear zones for internal waves are located along the characteristic paths or beams. Internal-wave bottom velocities and bottom stresses are intensified along seafloor slopes when  $c$  (equation 1) is approximately equal to bottom slope gradient  $\gamma$ . Essentially, under this condition energy is trapped along the seafloor, creating strong boundary layer motion and mixing. The nature of the bottom intensified flows and its potential for sediment resuspension and nepheloid layer generation were described by Cacchione and Drake (1986) and more recently by McPhee and Cacchione (1998).

On the PASTA shelf and upper slope regions off the central Italian coast, bottom slopes are typically gentle,  $\sim 0.05^\circ$  to  $0.3^\circ$  ( $\gamma \sim 0.0008$  to  $0.005$ ). In this region the inertial frequency  $f \sim 0.056$  cph. From equation (1) for near-inertial internal waves ( $\sigma \sim 0.07$  cph) and  $N \sim 6$  cph in the strong upper pycnocline,  $c \sim 0.007$ . This suggests that the near-coincidence of bottom gradient and angle of the energy flux for near-inertial internal waves might induce amplified bottom velocities and shears along the seafloor in this region.

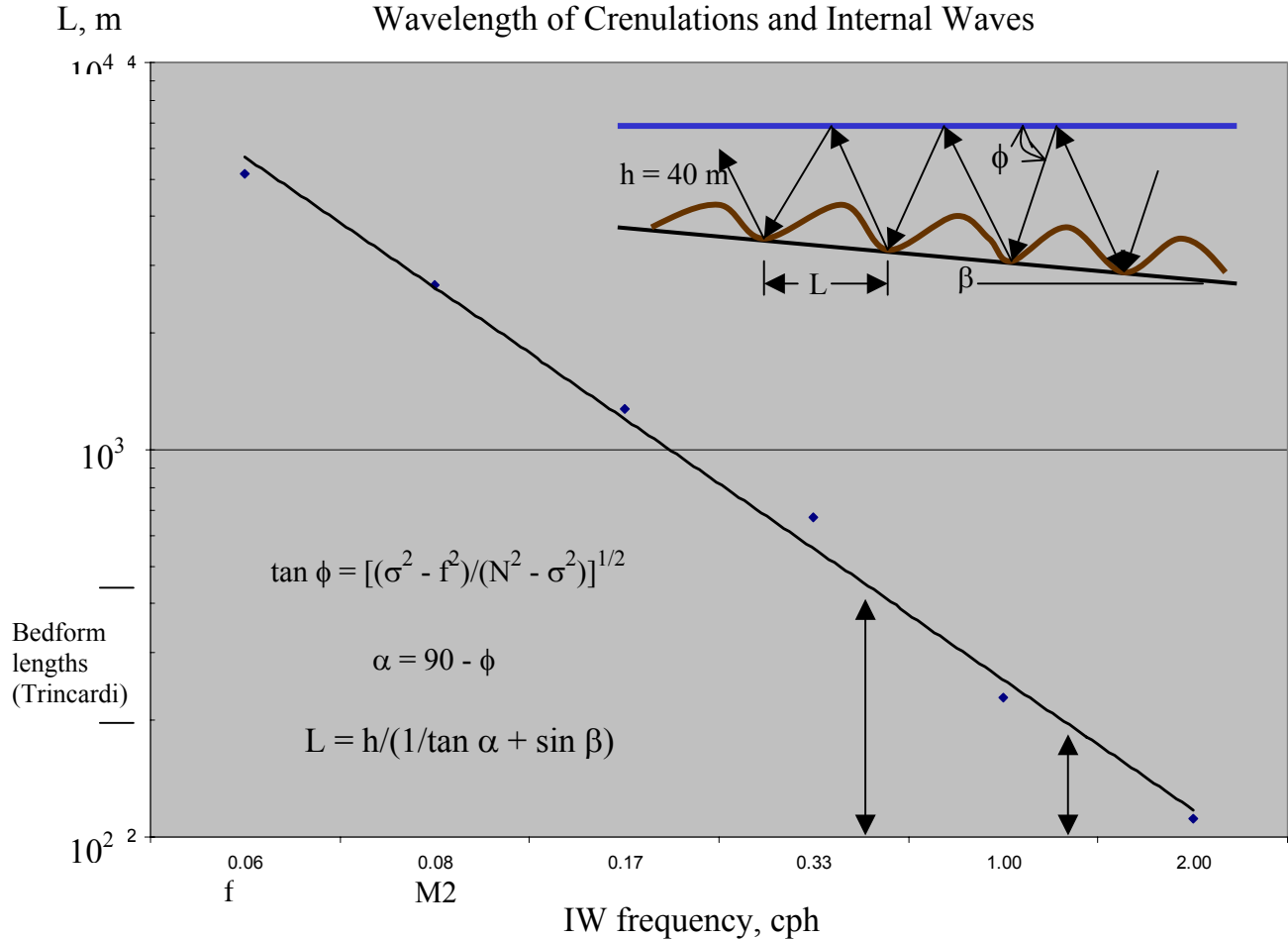
The relationship between internal wave periods and critical bottom slopes along the southern instrument line in PASTA is shown graphically in Figure 1. The near-inertial period  $T_f$  of about 17.8 hr is critical along a slope of  $\sim 0.07^\circ$  (or  $\gamma \sim 0.001$ ). As the slope gradient steepens, the critical internal wave period decreases. Also,  $T_{cr}$  increases for lower  $N$  at a given slope angle.



**Figure 1. Critical internal wave period at Pescara line calculated from Equation (1) assuming low slopes and  $\gamma/c = 1$ .**

Another interesting result comes from an analysis of the length scale for sequential intersections of  $c$  with a sloping bottom. If the internal waves reflect from the bottom such that the energy propagates upslope (the situation where  $\gamma/c < 1$ ) then we can define a length scale for the positions of intersection of  $c$  and the slope. It is at these intersection zones where we would expect increased bottom velocities and bed shear velocities. The repetition scale might relate to the spacing (wavelength) of bedforms in a manner similar to that for suborbital ripples and the scale of oscillatory water excursion amplitude at the bed caused by surface waves. The analysis for repetition length scale is summarized in Figure 2.

Assuming that internal waves propagate into the region of low slope ( $h$  is  $\sim$  constant over this section) containing seafloor bedforms, called crenulations in the PASTA region (Trincardi, personal comm.), and that  $\gamma/c < 1$ , then the diagram in the upper right depicts a series of intersections of  $c$  and the bottom slope. The length scale  $L$  of the intersections of  $c$  and slope as a function of internal wave frequency can be approximately established by the equation in the lower left side of Figure 2.



**Figure 2. Repetition length scale as a function of internal wave (IW) frequency  $\sigma$  for very low slopes  $\beta$  (depth  $h \sim$  constant over slope section). All angles in degrees. Wavelengths of crenulated bedforms are about 200 – 450 m (Trincardi, personal comm.).**

The results suggest that if the wavelengths of the crenulations, about 200 to 450 m, are in some way related to  $L$ , then only high-frequency internal waves would meet that criterion. Internal wave frequencies between about 0.4 cph - 1.4 cph would be required to produce repetition length scales equivalent to the crenulated bedforms. Since the current and temperature data show rather weak and intermittent energy in the high frequency portion of the internal wave band, it is unlikely that high frequency internal waves are responsible for the bedforms. Near-inertial internal waves are a more likely candidate because of their rather high observed bottom velocities, but how they might generate and maintain the bedforms remains unexplained. Continuing work on this process is underway.

## **IMPACT/APPLICATIONS**

Internal wave-induced bottom stresses might have a major influence on controlling erosion and deposition on shelves and slopes in the oceans and in the Mediterranean Sea. If the near-inertial internal waves are as energetic in the study areas as have been reported in other regions, they would be important processes for transporting fine sediment. They might also contribute to the formation and modification of bedforms that have been observed along the Adriatic shelf and on the outer shelf in the Gulf of Lyons.

Also, if high frequency internal waves intermittently shoal and break along the seafloor in the seasonal pycnocline, erosion and resuspension of bottom sediment might occur. This process could lead to dispersal of sediment, and generation of turbid bottom layers.

## **TRANSITIONS**

This work has applications for modeling of formation of sedimentary strata and structures on continental shelves. It may also have implications for sedimentation on certain continental shelves where turbulent shears from surface waves and other currents are relatively low (as compared with internal wave effects). The results and model can be integrated into more comprehensive sedimentation models that are under development by others (e.g., J. Syvitski and L. Pratson).

## **RELATED PROJECTS**

The internal wave work is being done in close collaboration with other EUROSTRATAFORM investigators: Dr. Andrea Ogston (U. of Washington), Dr Pere Puig and Dr. Alberto Palanques (both at Ciencies del Mar, Barcelona, Spain), Dr. Serge Berne (IFREMER, Brest, France), and Dr. Lincoln Pratson (Duke University).

This project is closely related to those EUROSTRATAFORM projects investigating morphology and surface sedimentation on continental shelves. The work is related to projects led by L. Pratson (Duke University), C. Nittrouer, and A. Ogston (both at University of Washington), J. Syvitski (INSTARR, University of Colorado), and M. Steckler (Lamont-Doherty Geological Observatory).

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## **PUBLICATIONS**

Puig, P., Palanques, A., Guillen, J., and D. Cacchione. 2002. The role of near-inertial internal waves in the sediment dynamics of Mediterranean continental shelves, EOS, Trans. Amer. Geophysical Union, Fall Annual Meeting, Abstract Number OS11C-0244.